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Designing a bedside table of wood furniture waste based on TRIZEE methodology

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Abstract
Environmental issues have become an important consideration to be included in business operations. One of the main environmental problems in the wood industry is the high production of wood waste and increasing scarcity and cost of raw materials. For this reason, companies need to utilize wood waste to reduce material costs and, at the same time, reduce the impact of waste on the environment. Converting wood waste into products that can be sold will increase its economic value. This research aims to identify the types of waste from a furniture company and reduce waste by designing various products made from wood waste. Wood chips are wood waste that have the potential to be reused. Waste wood chips from the materials station can be used to create bedside table products. The bedside table was chosen because of its high selling price, and the company could make it with ~~its~~ existing resources. Apart from that, the company still needs to expand its variety of bedside tables. The bedside table was designed using the TRIZEE method. TRIZEE is a method that combines eco-efficiency with 40 TRIZ principles, which can reduce environmental impacts in alignment with company goals. The design process resulted in 4 bedside table variations. Production capacity is estimated to produce 56 bedside tables per month. If scrap waste is successfully used as bedside table material. Apart from saving raw materials, the company will be able to reduce wood waste and gain greater profits from waste utilization.

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1. Introduction

Environmental issues have become a central topic of discussion, especially in academic fields, as there is widespread recognition that environmental challenges directly impact human daily life (Platcheck et al., 2008). Increasing public awareness of environmental issues requires companies to continuously increase awareness of environmental management. Because of this demand, many company stakeholders have begun integrating environmental management considerations into company's production activities (Wong et al., 2010). Environmental management means carrying out sustainable strategic planning activities through the maintenance management process and determining the direction and objectives of the management to be implemented (Kiurski et al., 2017). Environmental management aims to minimize waste disposed into the environment and reduce its impact on human health. The concept of socio-economic development and sustainable environmental management in the current era has been used as a basis for building plans that cover all human activities, especially in the manufacturing industry (Romeiro, 2012). The environmental management process is a long-term and sustainable activity so this process will have significant impacts and consequences for the company. Therefore, it is essential to identify the impact of implementing sustainable environmental management earlier to minimize or prevent the negative impacts and replace them with profitable investments for the company (Kiurski et al., 2017). Sustainable environmental management is done by efficiently reducing waste discharged into the environment and using natural resources (Deutz et al., 2013).

Waste is defined by the European Parliament and Council (2008) as anything in the form of chemicals or components that are disposed of or required to be disposed of into the environment. Waste in the form of gas is not defined as waste in the 2008 directive but is categorized as emissions. Waste comes from remaining raw materials or additional materials that could be used more efficiently. One way that can be used to reduce the amount of waste is to use it as a secondary raw material for producing goods.

Wood waste is one of the most common types of waste produced by the wood processing industry. This happens because the wood processing industry, both the primary wood processing industry (sawmills) and secondary wood processing industries such as the furniture and plywood industries, need higher efficiency in using materials. The sawmill industry produces wood waste as much as 40.48% of the raw materials used. In contrast, the furniture industry produces more waste, 54.81% of the total volume of raw materials (Purwanto, 2009). This number is enormous because over half of the raw materials are wasted. In Indonesia, there are 1,114 companies in the furniture industry sector spread across various regions, with a total production capacity of 2.9 million tons per year (Ministry of Industry of the Republic of Indonesia, 2021). The development of the furniture industry in Indonesia has experienced significant progress which can be seen in the increasing number of furniture exports in Indonesia. According to the data from the Ministry of Industry of the Republic of Indonesia (2021), the export performance of the furniture industry grew positively by 8.04% in the first quarter of 2021. The large number of furniture industries in Indonesia and their increasing production volumes correspond with the increasing amounts of wood waste. Generating large amounts of waste leads to financial losses for companies due to increased raw material costs while also harming the environment. For this reason, it is necessary to increase the efficiency of using raw materials or utilizing the resulting waste into products that have sales value. Wood waste can be used as a secondary resource to produce goods or as an energy source (Kim and Song, 2014). The raw material of logs can be replaced by using wood waste to save costs for transportation and reduce the amount of industrial waste discharged into the environment (Jungmeier et al., 2002).

Wood waste can be utilized using sustainable manufacturing principles in three fields, which include economic, environmental, and social. Utilization of wood waste in the economic sector can be by selling the waste directly to the wood processing industry or by processing the waste first into products with high selling value (Ng et al., 2014). The profits obtained by companies from direct waste sales are tiny and cannot be used to cover losses. Companies will gain greater profits if they process wood waste first to increase selling value, such as activated charcoal, charcoal briquettes, particle board, furniture made from waste, craft materials, furniture resin, etc. Activated charcoal is carbon material processed at high temperatures to create a highly porous structure that enhances its adsorption capacity. (Pari et al., 2009). Charcoal briquettes are activated charcoal from carbonization, which is further processed into briquettes (Hapid et al., 2018). Charcoal briquettes from sawdust can be used as an alternative energy source as a substitute for kerosene and firewood (Bahri, 2007). Particle board is a wood material made from sawdust and then compacted through a chemical process using high pressure and temperature (Ng et al., 2014). The result is pieces of plywood in various sizes, which can be further processed for interior needs, furniture, flooring and others (Cahyana, 2013). When viewed in terms of price, particle board is cheaper and quite popular. Particle boards will last longer if used in a well-ventilated space if it is not exposed to rain or moisture (Cahyana, 2013). Furniture made from waste is wood that can be used as a secondary raw material to produce furniture (Kim and Song, 2014). Waste from cutting the ends of logs can also be used to make crafts (Sumarno et al., 2016) and materials for making furniture with the addition of resin to increase the artistic value that can be sold (Souza et al., 2018).

Wood waste can be used as a secondary resource. A variety of products can be made from wood waste. Wood waste can also be used to produce furniture products such as tables, chairs and others from composite boards (Yang et al., 2007), gallon racks (Sari et al., 2024a), particle boards (Ng et al., 2014), resin furniture (Souza et al., 2018), natural energy sources (Abi Chahla et al., 2016), light brick mixtures (Purba et al, 2017), charcoal briquettes (Bahri, 2007), activated charcoal (Pari et al., 2009), crafts, souvenirs, decorations walls (Sutarman, 2016) and craft materials (Sumarno et al., 2016). From a social perspective, this will undoubtedly allow companies to add new production land. Opening new production land will require labour. Opening new job opportunities will reduce unemployment and increase people's welfare (Vinyes et al., 2013; Safarian et al., 2018). Wood waste from industrial processing can cause environmental damage if not appropriately managed. On the other hand, good waste management can improve nearby environmental problems. Recycling waste can minimize waste that must be disposed of in the environment (Sari et al., 2024b; Ripa et al., 2014).

PT X is a manufacturing company operating in the furniture industry in Semarang City, Central Java. The primary raw material used is *trembesi* wood. The products produced are furniture items such as coffee tables, bedside tables, standing lamps, dining tables, office chairs, hat hangers, etc. In its production process, PT X produces a lot of waste. Most wood waste comes from the sawmill and material processing process. It was recorded that the waste produced in one production period was 125 m^3 from a total of 230 m^3 of raw materials. Inappropriate waste management will cause environmental pollution (Hanisah et al., 2013). Currently, the company sells 80% of its wood waste, while storing the remaining 20% in warehouses for local production. Wood waste is sold at IDR 25,000 per m^3. By utilizing wood waste to create new products, the selling price of the new product may be higher than selling the wood waste itself. Additionally, the procurement of wood raw materials is reduced, thereby reducing transportation costs.

One of the products that is selling well on the market with little variation is the bedside table product. This product will also likely be made from waste wood chips because the dimensions are small. Increasing the variety of bedside table products will increase selling power to consumers. A bedside table is a small table designed to be placed next to the bed or elsewhere in the bedroom. Modern bedside tables usually have one or more drawers or shelves with small doors. This table is often used to place or store items that might be useful at night, such as a night light, alarm clock, reading material, telephone, glasses, drinks, or medicine. It is necessary to carry out a product design process to increase the variety of bedside table products. Therefore, this research hopes that companies will be able to diversify their products to utilize wood waste into products with sale value. Before producing a bedside table product, the company must conduct a series of production processes. One of the critical stages in the production process is the product design process. Previous researchers have employed various design methods, including Value Engineering (VE), which was applied to irrigation canal design. (El-Nashar and Elyamany, 2018), Quality Function Deployment (QFD) to design sand processing machines (Fan et al., 2017), Kansei Engineering (KE) to design rubber keypads in vehicles (Vieira et al., 2017) and *Teknologiya Resheniya Izobretatelskikh Zadatch* (TRIZ) to design water filters and washing machines (Sheng and Kok-Soo, 2010). Among these methods, TRIZ has the advantage of solving the most challenging problems with known but unknown causes and search directions (Zhang et al., 2003). This method provides a systematic way of innovation, solving problems creatively, ensuring that new possible solutions can be found and continue to produce innovations and create solutions to problems (Barry et al., 2010). TRIZ can also generate new ideas and use innovative principles to produce creative solutions (Chai et al., 2005).

The product design in this research is an eco-design carried out using the TRIZEE method, which uses 40 TRIZ principles combined with seven eco-efficiency elements that can reduce environmental impacts. This method has yet to be widely used in the product design process, especially for materials made from waste raw materials. Eco-efficiency is the ratio between added value and additional environmental impact or between economic and ecological performance indicators because the main goal is sustainable development (Caiado et al., 2017; Zhang et al., 2021). Eco-efficiency creates added value by meeting customer needs while reducing environmental impacts (Bartolomeo et al., 2003). TRIZEE method considers ecological aspects in the design process. These ecological aspects are translated into the design process using the 40 TRIZ principles. TRIZEE can be used for designing several types of products. This study focuses on designing furniture from recycled wood waste. Based on the literature study, the use of TRIZEE has not been widely studied and no previous research has utilized the TRIZEE methodology to design furniture products using wood waste. Highlighting this topic is crucial as it explores the potential of transforming waste into valuable products through an environmentally friendly production process, contributing to sustainable development and resource efficiency. This research aims to design a bedside table by utilizing wood furniture waste using the TRIZEE methodology. This research is expected to provide alternative product designs utilizing wood furniture waste, thereby diversifying products, increasing profitability, and reducing costs.

2. Literature review

2.1. Sustainable manufacturing

Sustainable manufacturing minimizes waste and reduces environmental impacts (Rao, 2013). The triple bottom line of sustainable development encompasses three main aspects: economic, environmental, and social. (Elkington, 1998). These three aspects are related, namely environmental and social issues that regulate environmental and natural resource protection laws (Rosen and Kishawy, 2012). Furthermore, in the environmental and economic aspects, there are regulations regarding subsidies/incentives and taxes/fines to promote efficiency and environmental management. The economic and social aspects include corporate social responsibility, business ethics, and worker protection. Sustainability indicators in sustainable manufacturing are also described in three aspects, with many factors influencing them (Pathak et al. 2017).

Sustainable manufacturing produces products that, during the production process, have a minimal negative impact on the environment; can save energy and natural resources; are safe for employees, society and consumers; are economically healthy (Menzel et al., 2010) and respect all workers socially and creatively (Pathak et al., 2017), however, it can maintain and/or improve product and process quality (Jawahir et al., 2013). Several factors have an essential role in influencing the manufacturing paradigm and encouraging the development of sustainable manufacturing concepts, such as product and system complexity, environmental concerns, lack of information regarding integration, and technological advances (Berkel et al., 2006). One of the efforts is to create a closed loop, where a circular production system focuses explicitly on revitalizing discarded products into new resources for production (Pathak et al., 2017), Sustainable manufacturing includes four product life cycle stages (pre-manufacturing, manufacturing, use and post-use). It follows the 6R methodology (reduce, reuse, recycle, recover, redesign and remanufacture) (Badurdeen and Jawahir, 2017; Zhang et al., 2013) such as reused second-hand fashion (Wicaksono et al., 2024), upcycled apparel (Sari et al., 2024c), and recycled electronic waste (Sari et al., 2023). The 6R concept is rooted in the cradle-to-cradle concept, a multigeneration life cycle with continuous and sustainable loop flow (Bradley et al., 2018). The product life cycle is the basis for sustainable manufacturing (Jawahir and Bradley, 2016). Sustainable production means making the best use of natural resources, minimizing waste and pollution, and investing in people to build a long-term successful business. Sustainable production begins at the design stage, where companies focus on producing products more efficiently, reducing waste, protecting the environment, and being socially responsible. Designers are the first to consider how a new product will be made and what materials it will be made of. Therefore, the design stage is critical to reduce costs, increase productivity, and develop innovative, sustainable consumer products. Product design determines the type and quantity of raw materials required, energy and waste generated during production, and whether the product can be recycled.

2.2. Element of eco-efficiency

Eco-efficiency arises from the desire to reduce negative things in management (Huppes and Ishikawa, 2005). Eco-efficiency is a clean production strategy, a preventive and integrated environmental management strategy continuously applied to the production process and product life cycle to reduce risks to humans and the environment (UNEP, 2004). The goal of eco-efficiency is to reduce material costs, energy, and the ecological impact of production throughout all stages of the life cycle (Wang et al., 2020; Wang et al., 2022). Eco-efficiency can be achieved by providing competitively priced goods and services that satisfy human needs and improve the quality of life while progressively reducing ecological impacts and reducing the intensity of resource use throughout the product life cycle to a level at least equal to the earth's estimated carrying capacity (WBCSD). Ecoefficiency is a tool for analysing economic inputs and outputs, resources and the environment of complex ecosystems (Chen and Liu, 2022). Eco-efficiency is the ratio between economic added value and environmental burden over a certain period (Chen and Liu, 2022; Islam et al., 2020; Tang et al., 2022), so it can be used to measure sustainability by looking at the achievement of economic and environmental targets (Findiastuti et al., 2020). Ecoefficiency is a tool for analysing economic inputs and outputs, resources and the environment of complex ecosystems (Chen and Liu, 2022). Proper use of waste will increase eco-efficiency values (Sari et al., 2023)

There are several essential factors in eco-efficiency, such as reducing the amount of materials used, reducing the amount of energy used, reducing pollution, increasing material recycling, maximizing the use of renewable natural resources, extending product life, and increasing service intensity (WBCSD, 2006). Elements of financial and/or environmental issues that concern stakeholders include the contribution to global warming, energy needs, waste, assets, liabilities, equity, income and expenditure, etc (UNCTAD, 2004). WBCSD (2006) defines four critical elements of ecoefficiency: reengineering processes, reassessing by-products, redesigning products, and rethinking markets. Eco-efficiency elements, according to Ichimura et al. (2009), include reducing material requirements, reducing energy intensity, reducing toxic materials, increasing material recycling, maximizing sustainable renewable resources, increasing product durability and increasing service intensity.

2.3. Product design

Design is a professional service that develops specifications and concepts to optimize product functionality, value, and aesthetics while benefiting both users and manufacturers. The goals in the product design process include utility, appearance, ease of maintenance, low cost and communication. Product design must meet two dimensions, namely ergonomics and aesthetics (Ulrich and Eppinger, 2011), which have the objectives of utility, appearance, ease of maintenance, low cost and communication. The approaches that can be taken in product design are original, adaptive, and variant design. Redesign is the term used for the three types of design above; redesign implies that the product has several criteria that must be updated because it fails to carry out its function or requires adjustments to its new function. For this reason, redesign is carried out as a new solution to solve problems (Otto, 2003).

Many methods can be used in the product design process, such as Value Engineering (VE), Quality Function Deployment (QFD), *Kansei* Engineering (KE) and *Theory Resheniya Izobretatelskikh Zadatch* (TRIZ). El-Nashar and Elyamany (2018) used VE to design canal tail irrigation, Fan et al. (2017) and Wang et al. (2017) used QFD to design sand processing machines and electric vehicles while KE to design vehicle rubber keypads (Vieira et al., 2017). TRIZ to design water filters and washing machines (Sheng and Kok-Soo, 2010), friction stir welding (Hsieh and Chen, 2010), mouse design (Yang and Chen, 2011), and low-carbon design (Ren et al., 2017). Value Engineering (VE) is an intensive, interdisciplinary problem-solving activity focused on increasing the value of the functions necessary to achieve the goals of any product, process, service, or organization. VE is an organized approach to analysing system functions, equipment, facilities, services and supplies to achieve consistency with required performance, quality and safety. The highest performance in VE is achieved primarily when the primary goal is increasing value rather than reducing costs. QFD is a concept that provides a means to translate customer requirements into appropriate technical requirements in each stage of product development, such as marketing strategy, planning, product design and engineering, prototyping, evaluation, production process development, production, and sales (Chan and Wu, 2002). KE emerged in Japan in the 1970s, intending to incorporate customer affective responses into the product design to translate human emotions into physical, measurable design specifications. The Japanese word "Kansei" is an intuitive mental action in the form of impressions, such as positive or negative images arising from external stimuli. This approach was developed to maximize satisfaction with their purchase (Vieira et al., 2017). TRIZ is a problem-solving method based on logic and data, not intuition, accelerating the ability to solve problems creatively. TRIZ can solve the most challenging problems with known but unknown causes and search directions (Zhang et al., 2003). This method provides a systematic way of innovation, solving problems creatively, ensuring that new possible solutions can be found and continue to produce innovations and create solutions to problems (Barry et al., 2010). TRIZ can also generate new ideas and use innovative principles to produce creative solutions (Chai et al., 2005). Števko et al. (2023), Vanko et al. (2023) and Ravinder Reddy et al. (2017) also carried out optimization of the tire building drum for passenger tires, assembly devices of automated workplaces and diffusion welding system, while Hassanijajini and Gardoni (2022) for innovation for building design. Serban et al. (2005) say that TRIZ is suitable for a design that considers environmental aspects (eco-design) to reduce the environmental impact of engineering processes (Livotov et al., 2018).

Several previous researchers have carried out the eco-design process using the TRIZ method with 40 TRIZ principles (Solid Creativity, 2024) as shown in Table 1, including studies by Vinodh et al. (2014), Spreafico (2022), Russo et al. (2017), Fayemi et al. (2016), Ben Moussa et al., (2019) and Cherifi et al. (2015). Vinodh et al. (2014) used TRIZ for innovation and sustainable product development. Spreafico (2022) developed a strategy for substituting materials in the eco-design process. Russo and Spreafico (2020) used a TRIZ-based eco-improvement guideline, while Russo et al. (2017) using based eco-design approach, Fayemi et al. (2016) and Ben Moussa et al., (2019) used based eco-design process. Russo et al. (2015) conducted eco-innovation in SMEs with TRIZ Eco-guidelines. Cherifi et al. (2015) developed a methodology for innovative eco-design using TRIZ. From several researchers who have carried out eco-design with TRIZ, eco-efficiency-based design has not been widely used for designing products made from waste, especially furniture waste. So, this research develops product designs made from furniture waste using the TRIZEE method, which is a product design method based on eco-efficiency.

Table 1. 40 TRIZ principles (Solid Creativity, 2024)

No	Principle	No	Principle
1	Segmentation	21	Skipping
2	Taking out	22	Blessing in disguise or turn lemon into lemonade
3	Local Quality	23	Feedback
4	Asymmetry	24	Intermediary
5	Merging	25	Self Service
6	Universality	26	Copying
7	Nested Doll	27	Cheap short-living objects
8	Anti-weight	28	Mechanical Substitution
9	Preminilary anti-action	29	Pneumatics and hydrolics
10	Preliminary action	30	Flexible shells and thin films
11	Beforehand cushioning	31	Porous material
12	Equipotentiality	32	Colour changes
13	The other way round	33	Homogenity
14	Spheroidality-Curvature	34	Discarding and recovering
15	Dynamics	35	Parameter objects
16	Partial or excessive actions	36	Phase transition
17	Another dimension	37	Thermal expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert atmosphere
20	Continuity of usefull action	40	Composite material

3. Research methods

This research was conducted at PT X and focuses on increasing the efficiency of using raw materials by utilizing wood waste. This research is classified as quantitative descriptive research focussing on providing an overview of the company's wood waste processing system. The quantitative approach involved manual measurement, observation, and calculation of wood waste.

The research is classified as an observational study because it employs direct observation to collect data on the object under study. Observations are carried out to classify wood waste by observing and recording the condition of the wood waste. This study utilizes both primary data from direct observations and secondary data from company records. Waste classification is carried out to make it easier to identify wood waste produced by PT X. The wood waste classification data is then used as a reference to determine alternative products that can be made. References for the utilization of wood waste are made by searching from existing literature. An alternative product is selected to be designed using Solidwork software while determining the waste type to be used.

3.1. Product design process

TRIZEE is a design method that integrates eco-efficiency elements with 40 TRIZ principles developed by Sheng and Kok-Soo (2010). TRIZEE is used in product design to increase efficiency and environmental value. Design methods generally have design phases, namely problem origin, problem exploration, solution and evaluation (Sheng and Kok-Soo, 2010).

3.1.1. Problem origin

Problems that trigger product design can come from internal and external factors of the company. Internal factors usually arise because management wants to increase product efficiency. External factors are problems that originate from the environment outside the company, including problems from consumers, the government, or other stakeholders related to the company.

3.1.2. Problem exploration

According to Altshuller (1996), a problem must be as simple as possible. Sheng and Kok-Soo (2010) used a tool called OFFERS to explore the problem. OFFERS is an abbreviation for several things that must be considered in evaluating a problem, which consists of objectives, functions, factors, effects, requirements, and specifications (Field, 2006). The eco-effectiveness elements used in designing products depend on the abilities of the designers. The eco-efficiency elements used in this research seven eco-efficiency elements used in the business sector include reducing material requirements for good or material reduction (MR), reducing energy intensity of goods or energy reduction (ER), reducing toxic dispersion (TR), enhancing material recyclability (RC), maximizing the sustainable use of renewable resources or resources sustainability (RS), extending product durability (PD), and increase the service intensity of goods or product service (PS) (ESCAP, 2009).

During the problem exploration stage, the manager must be able to determine the constraints used in the bedside table design process. To assist in selecting eco-efficiency elements, a tool called the eco-efficiency element ranking matrix is used.

The use of the eco-efficiency element ranking matrix will become easier if purpose, function and design factors are combined. Eco-efficiency Element Ranking Matrix is a tool in the form of a matrix used to determine the value of the seven eco-efficiency elements used in research. These seven elements are given weighted values according to the needs and objectives of the bedside table product design. The weighting of values depends on the information the manager has. The seven elements are placed in horizontal and vertical positions in the matrix. A value of 1 is given to one element subjectively if it is more important than other elements. Other elements are given a value of 0. The element with the highest value will be prioritized for use first in design considerations.

3.1.3. Solution generation

Solution generation employs two strategies: concept analysis and part analysis. Concept analysis is generally used to produce a new product. The resulting new concept will be different from previously existing concepts. In this research, concept analysis begins with interviews. Interviews were conducted with managers and designer employees of PT X. Interviews were conducted to explore the concepts used in furniture design, especially in bedside table products. Then, after conducting interviews, further information will be extracted through scientific journals to add references in designing bedside table products. Meanwhile, part analysis is used to develop the parts in a product. This process is carried out using reverse engineering techniques. Part analysis is used more often than concept analysis because the process can be carried out over a shorter period.

The core of the solution generation process is the use of TRIZEE design tools. TRIZEE provides structured solutions to existing problems by integrating 40 TRIZ principles with eco-efficiency elements, as shown in Table 2. After the eco-efficiency elements are determined at the problem exploration stage, solutions can be generated using the 40 TRIZ principles in the TRIZEE design tools. Part analysis and concept analysis are carried out continuously until the required design specifications are found.

Table 2. TRIZEE Design Tool (Sheng and Kok-Soo, 2010)

Eco efficiency element	TRIZ principles
MR	1, 4, 5, 6, 7, 8, 9, 13, 14, 16, 17, 18, 23, 26, 28, 29, 30, 31, 34, 35, 36, 37, 40
ER	1, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19, 20, 23, 25, 26, 28, 29, 31, 38, 39
TR	2, 9, 10, 11, 13, 16, 18, 21, 22, 23, 24, 30, 38, 39
RC	1, 2, 9, 10, 11, 12, 13, 15, 21, 22, 24, 29, 32, 33, 34, 35, 37
RS	3, 8, 18, 25, 28, 36, 37
PD	7, 9, 10, 11, 14, 39
PS	1, 4, 5, 6, 7, 9, 10, 14, 15, 17, 18, 24, 25, 27, 29, 30, 31, 32, 36, 38, 39

The 40 principles of TRIZ are a list of solutions that are widely known (Zhang et al., 2003). These solutions can inspire us to solve new problems and imagine innovative solutions.

3.1.4. Evaluation

The evaluation stage is used to determine improvements in environmental performance by comparing old products with new products or with competitor products. Evaluation of products being designed can be done using indicator calculation. The indicators proposed in the TRIZEE method are the eco-efficiency ratio and the X-factor. This indicator provides quantitative indicators to evaluate the level of eco-efficiency of a product.

Evaluation in this research uses one of the indicators which is the X-factor. The X-factor is used to measure quantitative progress in environmental efficiency implemented in bedside table products. The X-factor formula can be seen in Equation 1.

$$\text{X-Factor} = \frac{\text{Eco-efficiency of the new product}}{\text{Eco-efficiency of the old product}} \quad (1)$$

This research evaluates eco-efficiency by comparing X values between the old and new versions of the bedside table. There are 7 eco-efficiency elements used. The new version of the product will get a value of 1 if its efficiency level is higher than the old version, and a value of 0 if it is not more efficient. The old version is assigned a value of 1 if it is more efficient than the new version, and 0 if it is less efficient.

4. Results and discussion

4.1. Problem origin

The product that will be designed in this research is a bedside table. A bedside table is a small table designed to be placed next to the bed or elsewhere in the bedroom. Modern bedside tables usually have one or more drawers or shelves with small doors. Bedside tables are designed and manufactured in various styles, heights and materials that can be paired with other bed styles and bedroom furniture. In this research, bedside table products will be designed to increase product variety. The current products so far have no issues in terms of design; however, since the raw material used is logs, this has resulted in the production of a significant amount of wood waste. To reduce this large amount of waste, a variety of bedside table products will be designed using raw materials in the form of waste wood chips. In variance design, a product needs a reference for development. Apart from that, when designing a bedside table product, it is important to be matched it with other furniture it accompanies in the same room. Compatibility with other furniture in the room must be considered to ensure harmony. In this research, the product used as a reference is the bedside table product, which can be seen in Figure 1. This design has the main objective of achieving eco-efficiency element point 4 (ESCAP, 2009), namely increasing material recycling.

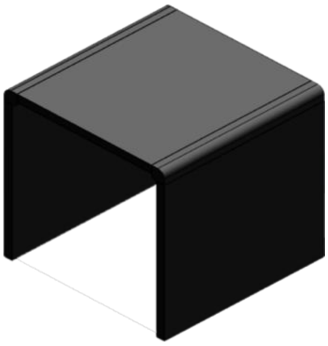

Fig. 1. Bedside table design reference

4.2. Problem exploration

After identifying the eco-efficiency elements, they are ranked based on their importance. The ranking was carried out to determine the priority use of eco-efficiency elements at the TRIZEE design tools stage. The eco-efficiency Element Ranking Matrix is a matrix used to determine the value of the seven eco-efficiency elements used in the research, as shown in Table 3. Then, the element ranking process is carried out, with the ranking order of the eco-efficiency elements shown in Table 3.

Table 3. Eco-efficiency elements ranking matrix

Eco-efficiency Element	MR	ER	TR	RC	RS	PD	PS	Total	Ranking
MR		0	0	1	1	1	1	4	3
ER	1		0	1	1	1	1	5	2
TR	1	1		1	1	1	1	6	1
RC	0	0	0		0	0	0	0	7
RS	0	0	0	1		1	1	3	4
PD	0	0	0	1	0		1	2	5
PS	0	0	0	1	0	0		1	6

Based on Table 3, the level of importance of one element to another element is as follows:

1. Material reduction (MR) is not more important than toxicity reduction (TR) and energy reduction (ER), but it is more important than the other four elements.
2. Energy reduction (ER) is not more important than toxicity reduction (TR) but is more important than the other five elements.
3. Toxicity reduction (TR) is the most important element.
4. Increase recyclability (RC) is the least important element.
5. Increasing resource sustainability (RS) is not more important than toxicity reduction (TR), energy reduction (ER), and material reduction (MR), but it is more important than the other three elements.
6. Increasing product durability (PD) is more important than increasing product service (PS) and recyclability (RC) but not more important than the other four elements.
7. Increasing product service (PS) is more important than increasing recyclability (RC) but not more important than the other five elements.

So, it can be said that toxicity reduction is the most important element, then energy reduction, material reduction, increased sustainable resources, increased product durability, increased product service, and the last but least important, increased recyclability.

4.3. Solution generation

4.3.1. Part analysis

The product that will be developed in this research is a bedside table product that the company has produced. This product was chosen because it has a high market and selling value and makes it possible to use wood chip waste as raw material. The product design can be seen in Figure 2. The design is deconstructed to identify its component parts.

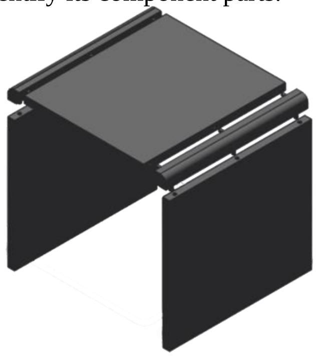

Fig. 2. Exploded reference design

The bedside table uses three types of parts in the form of one square tabletop, two side frames and two square legs. So, the product has 5 parts with a summary of the part analysis, which can be seen in Table 4.

Table 4. Summary of part analysis

No	Part Name	Amount (unit)	Size (mm)		
			L	W	T
1	Tabletop	1	500	420	24
2	Table leg	2	500	500	24
3	Side Frame	2	500	40	40

The right and left side panels function as the right and left legs to support the table so that it remains standing firmly. This table only has 2 legs but is as wide as the side of the table. This panel is rectangular. Then, the rectangular tabletop has the main function as a place to put items. Then, the right and left frames are used to connect the side panels to the tabletop using wooden pins.

4.3.2. Concept analysis

In concept analysis, the process of identifying product design ideas is carried out. In this research, identification was carried out by interviewing company employees and managers. From the results of the interview, it is known that, first, the product is made with a minimalist concept. The company considers the minimalist concept to be the most popular design. Then minimalist designs do not require a long process to produce products so they can be distributed to the market. The minimalist design concept describes comfort that arises from a good balance of color, shape and density of a space. Apart from prioritizing balance, the minimalist design concept is also a design concept that prioritizes efficiency.

The minimalist design concept aims to make products better without using many unnecessary things. It can be said that in the minimalist design concept, quality is more important than quantity. This means that it is better to make items that are quality, durable and have many functions compared to many types of furniture that are easily damaged and do not last long. Then, the most important thing about a minimalist design concept is the ability of this concept to appreciate simplicity. The minimalist design concept is a concept that respects space. Therefore, this concept prioritizes space over details for beauty. According to the minimalist design concept, space is part of beauty.

The second concept produced in interviews with companies is multifunctional, especially additional storage such as drawers, cupboards, and shelves. According to IKEA Indonesia Interior Designer Indy Anindita, Indonesian people are people who like collecting things. Old items that are no longer used, sometimes even damaged, can fill the room. From this statement, it is known that society's need is for storage. So, furniture with a multifunctional concept is one aspect that must be present in product design. In the Big Indonesian Dictionary, multifunctional is something that has various tasks or functions. It can be interpreted as multifunctional furniture as furniture that has more than one function in one object. Multifunctional furniture serves standard furniture purposes while providing additional value through its versatility. Because from an ergonomic and economic perspective, this furniture is in great demand. This type of furniture is suitable for narrow spaces such as apartments and simple houses. Multifunctional furniture can optimize the use of space, where the furniture can be used for more than one activity. In this research, 2 product functions must be highlighted. The first is the main function of the product itself, namely as place-to-place items that are often used or removed at night, such as books, laptops, glasses, and watches, and used as place-to-place bed decorations, such as flowers or night lights. The second function is an additional function where this function is used as a support to make the product more unique or appear to be ~~really~~ needed by customers. The additional function in this research is storage as a place to store goods. This storage space accommodates nighttime essentials, maintaining a tidy appearance when items are not in use. Space efficiency is very useful when using small spaces because, with efficient space, the use of indoor activities can also be utilized well and as optimally as possible. With limited living space, space efficiency is needed, so the use of multifunctional furniture will be very necessary for the many existing needs.

The third concept is unity. Based on the classification of types of waste that has been made, the type of waste used as raw material is waste that is large enough to be made into small blocks measuring around 50 mm x 150 mm with a thickness of 30 mm. At the initial stage of the production process, wood waste must be cut into small blocks. This is then done by uniting the small blocks into a blockboard. This block board looks like an ordinary square board that can be processed into furniture products like primary wood raw material. The TRIZEE design incorporates three concept analyses: minimalist, multifunctional, and unity. The bedside table is relatively simple, and the manufacturing process remains the same as before. This research focuses solely on the design aspects rather than the process. Therefore, technology aspects are not analyzed in this study.

4.4. TRIZEE design tools

The use of TRIZEE design tools aims to find generation solutions to design problems. TRIZEE is used to obtain product specifications to be designed. This specification is obtained by carrying out iterations of the part results or concept analysis. In this research, part analysis was not carried out again because it did not make significant changes to the product. This research focuses on designing products to add variety, not on designing new bedside table products. The result of the concept analysis is to obtain three categories of concepts that will be used in designing products, namely minimalism, unity and multifunction. TRIZEE design tools are the core of the TRIZEE design method. Table 5 in the Appendix shows the use of TRIZEE design tools in this research.

The unity product concept is linked to toxicity, energy, material reduction, and increasing recyclability. The toxicity reduction concept is linked to the principle of taking out and replacing regular adhesive with non-toxic adhesive when combining pieces of wood as raw material. Energy reduction concepts are linked to the principle of copying. The electrical energy consumption of the waste chip splitting machine is smaller than that of the log sawmill machine during the cutting process. Then, 40 TRIZ principal iterations were carried out on this concept, which resulted in three iterations. The first iteration produces the segmentation principle: changing or making the product into small blocks. Segmentation is used to divide an object into mutually independent parts (Liu, 2023). Then, the next iteration produces the copying principle to reproduce small blocks made from pieces of wood. The final iteration resulted in the merging principle for joining small blocks using non-toxic adhesive into a wide block board. Increasing recyclability is linked to blessing in disguise or turning lemon into lemonade because it uses wood waste materials to make the product. The principle of blessing in disguise or turning a lemon into lemonade relates to the utilization of detrimental factors (in particular, harmful impacts from the environment) to achieve positive effects (Zhang et al., 2003).

Furthermore, the multifunctional product is linked to material reduction and increasing resource sustainability. The material reduction concept is linked to the universality principle because making a part or object perform multiple functions will reduce material usage. Increasing resources sustainability concept because apart from being used as a place to store goods, the product can also be used for storing things. This principle is linked to local quality because the product has a different and more useful function than its main function. Local quality is used to make different parts of an object have different functions (Liu, 2023). This research's findings align with Li et al. (2023), who applied local quality principles to design multifunctional sanitation vehicles. Iterated is then done seven times. The first iteration produces the principle of local quality because the table will use additional storage as a function that is different and useful from its main function. The second iteration resulted in local quality principles for adding storage in the form of drawers. The third iteration produces local quality principles for adding storage in the form of cupboards or shelves. The fourth iteration produces the nested doll principle for placing the cupboard inside the table. Nest dolls are used to insert one object into another object, then insert the two combined objects into a third object, and so on (Liu, 2023). Then, the fifth iteration produces the nested doll principle for placing retractable drawers in the table. Then, the sixth iteration produces the nested doll principle for making drawers with sizes adjusted to the table size used as a reference. Then, the seventh iteration produces the nested doll principle for making cupboards that are adjusted in size to the table, which is used as a design reference. This research is in line with (Wang, 2020), which uses four inventive principles in designing multi-function tablets, one of which is a nest.

Then, the minimalist concept is associated with the concept of toxicity and material reduction as an option in the eco-efficiency element. This is because minimalist product design aims to use materials efficiently and effectively, so the process used to make the product is also more effective. Then, taking out was chosen in the 40 principles of TRIZ because minimalist design aims to eliminate materials or parts that are not important, so only select the parts (or properties) that are needed (Russo and Spreafico, 2020). Then, iterated on the 40 TRIZ principles, the result was the color change category, namely, in minimalist design, you need to use natural colors. IAWF natural dyes were chosen as environmentally friendly dyes (Darmono, 2010).

4.5. Solution (design results)

By using the results of the TRIZEE design tools, the design process was carried out. The specifications obtained are used as a reference for designing products. From the design process, four types of design alternatives were obtained as the result. The design results can be seen in Figure 3.

There are four designs produced to add variety to the company's bedside table designs. These four types of designs are different from each other. Even though they are different, the overall variations produced are still following the established concept, namely minimalism multifunctional, which in this case is the addition of storage in the form of cupboards (shelves) and drawers, as well as unity.

The first alternative product design is a bedside table product design that has one open cupboard and one closed drawer. The general design of this product is almost the same as the reference product. The difference lies in the addition of drawers and cupboards. The size of the drawer is adjusted to the length and width of the table. Drawer height is 100 mm. This size is the standard drawer size for products made by the company. The cupboards made with this product have length and width sizes that are adjusted to the dimensions of the table. The height is taken from the Ministry of Education and Culture's standard for the height of a bookshelf, namely 250 mm.

The second alternative product design is a bedside table design, which has one open drawer and 1 open cupboard. The dimensions of the drawers and cupboards are the same as the first bedside table product. There are not many differences between the first and second product designs. The only difference lies in the drawer. The first product design has a closed drawer that can be opened by pulling it out, while the second product design has an open drawer that cannot be pulled out. This drawer is designed as a compact cabinet with reduced height.

The third alternative product design has slight differences from the first and second products. This difference lies on the side where there is no frame connecting the side panel to the top panel. The square table features identical storage dimensions to the first design.

The fourth product design alternative is a product that has slight differences from the third product design with almost the same size and dimensions. The size of the storage and the shape of the storage are also the same, in the form of a closed drawer that can be pulled out and an open cupboard. The fourth design features a crown molding on top, distinguishing it from the third design's flat surface. This is done to add to the aesthetics of the product. An additional function for this part, apart from aesthetics, is also to prevent items placed on the table, such as bed lamps and flowers, from falling onto the floor due to regular shaking.

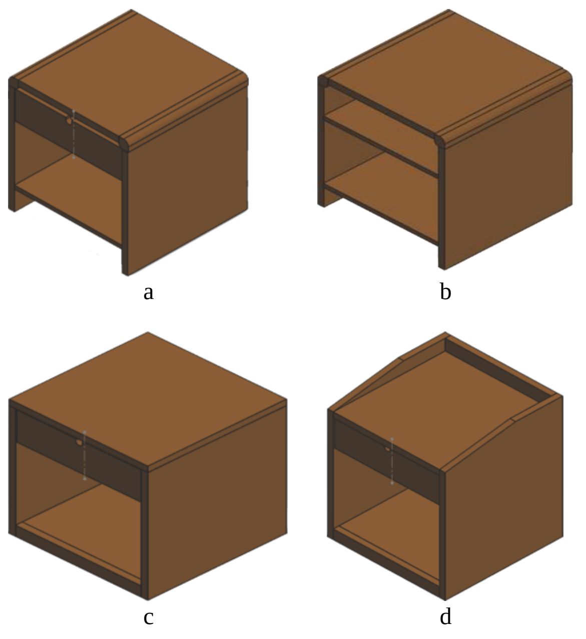

Fig. 3. Design results: a) Alternative 1, b) Alternative 2, c) Alternative 3, and d) Alternative 4

Survey is conducted to determine the best alternative design. Based on survey of buyers, the best alternative design chosen is alternative 1. The evaluation and further analysis are carried out based on alternative 1.

4.6. Evaluation

The evaluation carried out in this research was by looking for the X value (Equation 1), which compares the eco-efficiency element values of old version of the products with new version of products chosen which is alternative 1. There are 7 eco-efficiency elements used. A new product will get a score of 1 if it is more efficient than the old product and will get a score of 0 if it is not more efficient than the old product. Then, the old product will get a value of 1 if it is more efficient than the new product and will get a value of 0 if it is not more efficient than the new product, as shown in Table 6.

Table 6. Eco-efficiency the new and old product

Eco-efficiency Element	Old Product	New Product	Information
MR	1	0	The material volume of old products is less than new products
ER	0	1	The electrical energy consumption of the waste chip splitting machine is smaller than that of the log sawmill machine
TR	0	1	The new product does not use toxic materials
RC	0	1	The new product uses waste wood chips as raw material, while the old product uses logs.
RS	1	1	New and old products use wood as raw material.
PD	1	0	Old products use solid wood, while new products use wooden block boards made from small blocks.
PS	0	1	Apart from being a bedside table, the new product also provides additional functions in the form of storage.

The evaluation stage provides an overview for the company about the improved environmental performance provided by the new product. The material reduction (MR) element is given a value of 1 for old products and a value of 0 for new products because new products increase material use due to additional parts in the form of back panels, drawers and middle panels. In the energy reduction (ER) element, the old product gets a value of 0, and the new product gets a value of 1 because the old product uses a sawmill to process its raw materials with greater electricity consumption compared to processing the new product's wood chip waste using a split machine. In the toxic reduction (TR) element, old products are given a value of 0 and new products are given a value of 1 because the new products use environmentally friendly water-based dyes. In the increased recyclability (RC) element, new products are given a value of 1 because they use wood waste as raw material, while old products use logs. In the increased resource sustainable (RS) element, both products are given a value of 1 because the raw material used is wood, which is a renewable and sustainable resource. In the increased product durability (PD) element, a value of 1 is given to the old product because it uses raw logs, which are sturdier than the raw material for the new product, which is a combination of wood scrap waste. Finally, the increased product service (PS) element is given a value of 1 for new products because of the additional function provided in the form of storage. As a result, the old product gets a score of 3, and the new product gets a score of 5. From equation 1, the X factor value is 1.67; this shows that the new product is more eco-efficient than the old product. This result shows that from the aspects of cost, market value and environmentally friendly costs, new products are better than old products because eco-efficient value creation is characterized by a combined analysis of costs, market value and environmentally friendly costs (Vogtlander et al., 2017). Efficient shows that the new product uses minimal materials and energy. Eco-efficient refers more to eco-effective because it is more oriented towards optimal value rather than minimum cost (Wever and Vogtländer, 2013).

4.7. Production capacity

The raw material used in making bedside tables is waste wood chips from fabrication. These pieces of wood waste are large enough to be reprocessed. The company does not include this material as primary raw material because of its low quality. The quality of the wood is lower because the size of the wood is smaller, and the water content is higher, which means it breaks more easily. This condition is because most of the wood scrap waste is the outer part of the wooden board. The number of pieces of wood waste from the material processing process is relatively large, so it needs to be utilized.

As an illustration, the company purchased 104 pieces of wood with a volume of 35.85 m3 for one month's needs. The wood chip waste produced was 4,056 m^3. This waste is equivalent to the volume of 11 logs. By utilizing this scrap waste, the company will save at least the cost of 11 logs. This is an advantage worth considering for companies. Apart from being profitable in terms of profit, the company has also reduced the number of trees that have to be cut down from the wild. The company can use waste wood chips to make 89 block boards measuring 1,200 mm x 600 mm x 30 mm (company standard). By using data on length and width dimensions without considering thickness, the availability of block boards is 64,080,000 mm^2, and the need for block boards for a bedside table is 1,116,304 mm^2 as in Table 7, it is possible to calculate the number of bedside tables that the company can make. So, the production capacity for bedside table products is around 56 pieces per month.

A cost-benefit analysis (CBA) can be used to measure the financial feasibility of utilizing waste in new products (Chaerul and Rahayu, 2019). CBA is a measurement method for determining the value of benefits obtained from a process/activity (Misuraca, 2014). Several researchers also use CBA to measure the effectiveness of waste management, such as waste management in Romania (Ghinea and Gavrilescu, 2016), food waste management in Singapore (Ahamed et al., 2016), solid waste management (Martinez-Sanchez et al., 2015).

Table 7. Dimensional requirements for bedside tables

Part Name	Thickness (mm)	Length (mm)	Width (mm)	Area (mm^2)
Top Panel	24	500	420	210,000
Right Panel	24	476	500	238,000
Left Panel	24	476	500	238,000
Back Panel	24	476	452	215,152
Middle Panel	24	476	452	215,152
Total				1,116,304

The selling price of wood waste is IDR. 25,000 per sack. Meanwhile, the company's selling price for bedside tables is between IDR 2,000,000 to IDR 3,000,000. Because the raw material used is wood waste, the temporary selling price is IDR 1,000,000. It can be assumed that one sack of wood can be used to make one bedside table. Converting wood waste into products increases profits by 39% compared to selling raw waste. However, this profit percentage is only seen from the aspect of material use without considering other cost aspects. Including additional cost factors would reduce potential profits. However, the profits obtained are still much greater than selling it in the form of waste. Apart from providing economic benefits, this utilization will also reduce furniture industry waste to move towards a circular economy (Hartini et al., 2021).

5. Summary and conclusion

This research resulted in a bedside table product design using waste wood chips as raw material. The design was carried out by combining minimalist, multifunctional and unity concepts with the TRIZEE method. The minimalist concept is associated with the concept of toxicity reduction by using environmentally friendly dyes and the concept of material reduction by eliminating unimportant parts thus saving raw materials. The multifunction concept is associated with material reduction and sustainable resources by utilizing products not only for a table, but also as a place to store goods. The unity product concept is linked to toxicity reduction by replacing adhesive with non-toxic adhesive; energy reduction by using lower energy of cutting machine; material reduction by utilizing wood waste as raw materials; and increased recyclability by utilizing wood waste that can optimize the existing resources. Converting wood waste into products increases profits by 39% compared to selling raw waste. Based on the resulting design, with 4,056 m^3 of wood scrap waste, equivalent to the volume of 11 logs, it can produce 56 units of bedside table products. Apart from providing large profits for the company, replacing logs with wood waste cuts is also reducing raw material costs and an effort to save on the use of felled wood from the forest. The calculation of profits in this research only involves saving costs from using wood log materials; for future research, it can be developed by calculating other costs involved in making this product.

As with all research, this study has several limitations to consider in interpreting the result. First, this research still focuses on designing wooden furniture based on wood chip waste; further research can design another type of furniture besides wood and can utilize other types of waste such as powder, bark, end pieces, etc. Second, the design concept and solution generation is generated based on interview that is conducted with managers and designer employees of PT X. The design chosen by the company may be different from the design desired by consumers. Future research is by combining the TRIZEE using Green QFD to capture the voice of customers. It is possible to create a better product design that can capture comprehensive customer desires.

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Reference

Abi Chahla, G., Zoughaib, A., Tran, C.-T., and Farel, R., 2016. Is wood waste only for burning? A methodology for best pathway identification of waste recovery. Computer Aided Chemical Engineering, 38, 199–204, DOI:10.1016/B978-0-444-63428-3.50038-2

Ahamed, A., Yin, K., Ng, B. J. H., Ren, F., Chang, V.-C., and Wang, J.-Y., 2016. Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives. Journal of Cleaner Production, 131, 607–614, DOI:10.1016/j.jclepro.2016.04.127

Altshuller, G., 1996. And Suddenly the Inventor Appeared: TRIZ, the Theory of Inventive Problem Solving (2nd ed.). Worcester: Technical Innovation Center, Inc.

Badurdeen, F., and Jawahir, I. S., 2017. Strategies for value creation through sustainable manufacturing. Procedia Manufacturing, 8, 20–27, DOI:10.1016/j.promfg.2017.02.002.

Bahri, S., 2007. Pemanfaatan limbah industri pengolahan kayu untuk pembuatan briket arang dalam mengurangi pencemaran lingkungan di Nanggroe Aceh Darussalam. Universitas Sumatera Utara.

Barry, K., Domb, E., and Slocum, M. S., 2010. TRIZ-what is TRIZ? The TRIZ journal, 603–632.

Bartolomeo, dal M., dal Maso, D., De Jong, P., Eder, P., Groenewegen, P., Hopkinson, P., James, P., Nijhuis, L., Örninge, M., and Scholl, G., 2003. Eco-efficient producer services—what are they, how do they benefit customers and the environment and how likely are they to develop and be extensively utilised? Journal of Cleaner Production, 11(8), 829–837, DOI:10.1016/S0959-6526(02)00157-9.

Ben Moussa, F. Z., Essaber, F. E., Benmoussa, R., and Dubois, S., 2019. Enhancing eco-design methods using TRIZ tools: The case of ECOFAIRE. New Opportunities for Innovation Breakthroughs for Developing Countries and Emerging Economies: 19th International TRIZ Future Conference, TFC 2019, Marrakesh, Morocco, 350–367.

Berkel, R., Willems, E., and Lafleur, M., 2006. The relationship between cleaner production and industrial ecology. Journal of Industrial Ecology, 1(1), 51–66, DOI: 10.1162/jiec.1997.1.1.51.

Bradley, R., Jawahir, I. S., Badurdeen, F., and Rouch, K., 2018. A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation. Resources, Conservation and Recycling, 135, 141–149, DOI: 10.1016/j.resconrec.2018.01.017.

Cahyana, B. T., 2013. Papan partikel dari serbuk kayu dan limbah penyulingan kulit kayu gemor (alseodaphne spp.). Jurnal Riset Industri Hasil Hutan, 5(2), 9–20, DOI: 10.24111/jrihh.v5i2.1214.

Caiado, R. G. G., de Freitas Dias, R., Mattos, L. V., Quelhas, O. L. G., and Leal Filho, W., 2017. Towards sustainable development through the perspective of eco-efficiency-A systematic literature review. Journal of Cleaner Production, 165, 890–904, DOI:10.1016/j.jclepro.2017.07.166.

Chaerul, M., and Rahayu, S. A., 2019. Cost Benefit analysis for developing municipal solid waste treatment facility: case study of Pekanbaru city. Journal of Natural Resources and Environmental Management, 9(3), 710–722, DOI:10.29244/jpsl.9.3.710-722

Chai, K.-H., Zhang, J., and Tan, K.-C., 2005. A TRIZ-based method for new service design. Journal of Service Research, 8(1), 48–66, DOI: 10.1177/1094670505276683

Chan, L.-K., and Wu, M.-L., 2002. Quality function deployment: A literature review. European Journal of Operational Research, 143(3), 463–497, DOI: 10.1016/S0377-2217(02)00178-9

Chen, Y., and Liu, L., 2022. Improving eco-efficiency in coal mining area for sustainability development: An emergy and super-efficiency SBM-DEA with undesirable output. Journal of Cleaner Production, 339(121), 130701, DOI: 10.1016/j.jclepro.2022.130701.

Cherifi, A., Dubois, M., Gardoni, M., and Tairi, A., 2015. Methodology for innovative eco-design based on TRIZ. International Journal on Interactive Design and Manufacturing (IJIDeM), 9, 167–175, DOI: 10.1007/s12008-014-0255-y

Darmono, D., 2010. Aplikasi teknik finishing mebel dengan bahan berbasis ramah lingkungan. INOTEKS: Jurnal Inovasi Ilmu Pengetahuan, Teknologi, dan Seni, 14(2), 208-223, DOI:10.21831/ino.v14i2.2297

Deutz, P., McGuire, M., and Neighbour, G., 2013. Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers. Journal of Cleaner Production, 39, 117–128, DOI: 10.1016/j.jclepro.2012.08.035.

El-Nashar, W. Y., and Elyamany, A. H., 2018. Value engineering for canal tail irrigation water problem. Ain Shams Engineering Journal, 9(4), 1989–1997, DOI: 10.1016/j.asej.2017.02.004.

Elkington, J., 2010. Cannibals with forks: the triple bottom line of 21st century business. Choice Reviews Online, 36(07), 3997-3997, DOI: 10.5860/choice.36-3997.

ESCAP, 2009. Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activites on the Environment. United Nations.

Fan, S., Xiong, J., Xu, T., Chen, S., and Zhang, W., 2017. QFD design of machine-made sand based on independent/decomposition axiom. Procedia engineering, 174, 442–448, DOI: 10.1016/j.proeng. 2017.01.164.

Fayemi, P.-E., Vitoux, C., Schöfer, M., and Bersano, G., 2016. Using TRIZ to combine advantages of different concepts in an eco-design process. Sustainable Design and Manufacturing, 52, 513–523., DOI: 10.1007/978-3-319-32098-4_44

Field, N. W., 2006. Introduction to Engineering Design. Clayton, Vic. : Monash Melbourne, Dept of Mechanical Engineering.

Findiastuti, W., Singgih, M. L., and Anityasari, M., 2020. System-dynamic simulation application on farming eco-efficiency measurement. Journal of Physics: Conference Series, 1569(3), 1–8, DOI: 10.1088/1742-6596/1569/3/032021.

Ghinea, C., and Gavrilescu, M., 2016. Costs analysis of municipal solid waste management scenarios: IASI–Romania case study. Journal of Environmental Engineering and Landscape Management, 24(3), 185–199, DOI: 10.3846/16486897.2016.1173041

Hanisah, K., Kumar, S., and Tajul, A., 2013. The management of waste cooking oil: a preliminary survey. Health and the Environment Journal, 4(1), 76-81

Hapid, A., Muthmainnah, M., and Ahmad, A., 2018. Karakteristik briket arang dari campuran tempurung kelapa dan serbuk gergaji kayu palapi (Heritiera Sp). Forest Sains, 15(2), 47–57.

Hartini, S., Wicaksono1, P. ., Rizal, M. ., and Hamdi, M., 2021. Integration lean manufacturing and 6R to reduce wood waste in furniture company toward circular economy Integration lean manufacturing and 6R to reduce wood waste in furniture company toward circular economy. IOP Conference Series: Materials Science and Engineering.

Hassanijajini, H., and Gardoni, M., 2022. The importance of preparing customized TRIZ matrix to accelerate the innovation for design buildings. IFIP International Conference on Product Lifecycle Management, 453–462.

Hsieh, H. T., and Chen, J. L., 2010. Using TRIZ methods in friction stir welding design. The International Journal of Advanced Manufacturing Technology, 46, 1085–1102, DOI: 10.1007/s00170-009-2172-y

Huppes, G., and Ishikawa, M., 2005. A framework for quantified eco-efficiency analysis. Journal of industrial ecology, 9(4), 25–41, DOI: 10.1162/108819805775247882

Ichimura, M., Nam, S., Bonjour, S., Rankine, H., Carisma, B., Qiu, Y., and Khrueachotikul, R., 2009. Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activities on the Environment. "Greening of economic growth" series, Retrieved from https://sustainabledevelopment.un.org/content/documents/785eco.pdf

Islam, M. S., Ferdousy, S., Afrin, S., Ahsan, M. N., Haider, M. Z., and Das, D. K., 2020. How does farmers' field schooling impact eco-efficiency? Empirical evidence from paddy farmers in Bangladesh. China Agricultural Economic Review, 12(3), 527–552, DOI:10.1108/CAER-12-2018-0239

Jawahir, I. S., Badurdeen, F., and Rouch, K. E., 2013. Innovation in sustainable manufacturing education. Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

Jawahir, I. S., and Bradley, R., 2016. Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. Procedia CIRP, 40, 103 – 108, DOI: 10.1016/j.procir.2016.01.067

Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C., and Richter, K., 2002. Allocation in lca of wood-based products experiences of cost action E9 part i. methodology. The International Journal of Life Cycle Assessment, 7, 290–294, DOI: 10.1007/BF02978686

Kim, M. H., and Song, H. B., 2014. Analysis of the global warming potential for wood waste recycling systems. Journal of Cleaner Production, 69, 199–207, DOI: 10.1016/j.jclepro.2014.01.039

Kiurski, J. S., Marić, B. B., Oros, I. B., and Kecić, V. S., 2017. The ecodesign practice in Serbian printing industry. Journal of Cleaner Production, 149, 1200–1209, DOI: 10.1016/j.jclepro.2017.02.193

Li, S., Wang, P., Ning, J., Chong, W., and Cui, X., 2023. Innovative design of multi-functional sanitation vehicle based on TRIZ theory. Proceedings of the 2nd International Conference on Information, Control and Automation, Chongqing, China, DOI: 10.4108/eai.2-12-2022.2328011

Liu, X., 2023. Research on the design of children's growth-oriented furniture based on the TRIZ theory. Journal of Humanities, Arts and Social Science, 7(3), 563–569, DOI: 10.26855/jhass.2023.03.016.

Livotov, P., Sekaran, A. P. C., Mas'udah, A. S., and Sayyareh, S., 2018. Environmental problems and inventive solution principles in process engineering. Proceedings of the 18th TRIZ Future Conference Towards automated inventions for smart industries, Strasbourg, France, 27-36

Martinez-Sanchez, V., Kromann, M. A., and Astrup, T. F., 2015. Life cycle costing of waste management systems: Overview, calculation principles and case studies. Waste management, 36, 343–355, DOI: 10.1016/j.wasman.2014.10.033

Menzel, V., Smagin, J., and David, F., 2010. Can companies profit from greener manufacturing? Measuring Business Excellence, 14(2), 22–31, DOI: 10.1108/13683041011047830.

Ministry of Industry of the Republic of Indonesia, 2021. Kembali Tumbuh di TW-I 2021, Industri Furnitur Genjot Investasi dan Ekspor.

Misuraca, P., 2014, The effectiveness of a costs and benefits analysis in making Federal Government decisions: A literature review. Center for National Security, The MITRE Corporation.

Ng, R., Shi, C. W. P., Tan, H. X., and Song, B., 2014. Avoided impact quantification from recycling of wood waste in Singapore: an assessment of pallet made from technical wood versus virgin softwood. Journal of Cleaner Production, 65, 447–457, DOI: 10.1016/j.jclepro.2013.07.053

Otto, K. N., and Wood, K. L., 2001. Product Design: Techniques in Reverse Engineering and New Product Development. Prentice Hall, Inc, New Jersey, USA.

Pari, G., Widayati, D. T., and Yoshida, M., 2009. Mutu arang aktif dari serbuk gergaji kayu. Jurnal Penelitian Hasil Hutan, 27(4), 381–398, DOI: 10.20886/jphh.2009.27.4.381-398

Pathak, P., Singh, M. P., Sharma, P., 2017. Sustainable manufacturing: an innovation and need for future. Proceedings of International Conference on Recent Innovations in Engineering and Technology, Jaipur, India, 978–993.

Platcheck, E. R., Schaeffer, L., Kindlein Jr, W., and Cândido, L. H. A., 2008. EcoDesign: case of a mini compressor re-design. Journal of Cleaner Production, 16(14), 1526–1535, DOI:10.1016/j.jclepro.2007.09.004

Purba, R. E. S., Irwan, I., and Nurmaidah, N., 2017. Pemanfaatan limbah serbuk gergaji kayu sebagai subtitusi campuran bata ringan kedap suara. Journal of Civil Engineering Building and Transportation, 1(2), 87–95. DOI: 10.31289/jcebt.v1i2.1679.

Purwanto, D., 2009. Analisa jenis limbah kayu pada industri pengolahan kayu di Kalimantan Selatan. Jurnal Riset Industri, 14–20, DOI: 10.24111/jrihh.v1i1.864

Rao, P. N., 2013. Sustainable manufacturing - principles, applications and directions. 28th National Convention of Production Engineers & National

Seminar on Advancements in Production and Operations Management, Jaipur, India, 1–14.
Ravinder Reddy, N., Satyanarayana, V. V., Prashanthi, M., and Suguna, N., 2017. Application of TRIZ methodology in diffusion welding system optimization. Management Systems in Production Engineering, 25(4), 237–240, DOI: 10.1515/mspe-2017-0033
Ren, S., Gui, F., Zhao, Y., Xie, Z., Hong, H., and Wang, H., 2017. Accelerating preliminary low-carbon design for products by integrating TRIZ and Extenics methods. Advances in Mechanical Engineering, 9(9), DOI: 10.1177/1687814017725461
Ripa, M., Buonaurio, C., Mellino, S., Fiorentino, G., and Ulgiati, S., 2014. Recycling waste cooking oil into biodiesel: A life cycle assessment. International Journal of Performability Engineering, 10(4), 347–356,DOI :10.23940/ijpe.14.4.p347.mag.
Romeiro, A. R., 2012. Sustainable development: an ecological economics perspective. Estudos Avançados, 26(74), 65–92,
Rosen, M. A., and Kishawy, H. A., 2012. Sustainable manufacturing and design: concepts, practices and needs. Sustainability, 4(2), 154–174, DOI: 10.3390/su4020154.
Russo, D., Rizzi, C., and Fayemi, P.-E., 2017. An industrial application of a triz based eco-design approach. sustainable design and manufacturing 2017: Selected papers on Sustainable Design and Manufacturing, 909–918, Springer, DOI: 10.1007/978-3-319-57078-5
Russo, D., Schöfer, M., and Bersano, G., 2015. Supporting ECO-innovation in SMEs by TRIZ eco-guidelines. Procedia engineering, 131, 831–839, DOI: 10.1016/j.proeng.2015.12.388
Russo, D., and Spreafico, C., 2020. TRIZ-based guidelines for eco-improvement. Sustainability, 12(8), 3412, DOI: 10.3390/su12083412
Safarian, S., Sattari, S., and Hamidzadeh, Z., 2018. Sustainability assessment of biodiesel supply chain from various biomasses and conversion technologies. BioPhysical Economics and Resource Quality,.3(2), DOI: 10.1007/s41247-018-0039-2.
Sari, D. P., Hartini, S., Azzahra, F., Arsiwi, P., and Prayoga, R. G., 2024a. Modular-based multifunctional product design made from furniture waste toward the circular economy : case in indonesia, 32(3),303–316, DOI 10.2478/mspe-2024-0029
Sari, D. P., Masruroh, N. A., and Asih, A. M. S., 2023. Eco-efficiency comparative analysis of informal and formal smartphone recycling practices using life cycle assessment. International Journal on Advanced Science, Engineering & Information Technology, 13(3), 1108–1117, DOI:10.18517/ijaseit.13.3.17452
Sari, D. P., Masruroh, N. A., and Asih, A. M. S., 2024b. Economic and environmental benefits of e-waste management networks design in Yogyakarta Province , Indonesia. Journal of Industrial Engineering and Management, 17(1), 292–320, DOI: 10.3926/jiem.6651.
Sari, D. P., Wicaksono, P. A., and Ainiyah, A. N., 2024c. Creating a fashion circular economy : factors influencing consumer intentions to purchase upcycled apparel. Kexue Tongbao/Chinese Science Bulletin, 69(1), 763–778,
Serban, D., Man, E., Ionescu, N., and Roche, T., 2005. A TRIZ approach to design for environment. In: Talabă, D., Roche, T. (eds) Product Engineering. Springer, Dordrecht, DOI: 10.1007/1-4020-2933-0_6
Sheng, I. L. S., and Kok-Soo, T., 2010. Eco-efficient product design using theory of inventive problem solving (TRIZ) principles. American Journal of Applied Sciences, 7(6), 852-858, DOI:10.3844/ajassp.2010.852.858.
Solid Creativity, 2024. 40 TRIZ Principles, Retrieved from: https://www.triz40.com/aff_Principles_TRIZ.php
Souza, A. M., Nascimento, M. F., Almeida, D. H., Silva, D. A. L., Almeida, T. H., Christoforo, A. L., and Lahr, F. A. R., 2018. Wood-based composite made of wood waste and epoxy based ink-waste as adhesive: A cleaner production alternative. Journal of Cleaner Production, 193, 549–562, DOI: 10.1016/j.jclepro.2018.05.087
Spreafico, C., 2022. Can TRIZ (Theory of Inventive Problem Solving) strategies improve material substitution in eco-design? Sustainable Production and Consumption, 30, 889–915, DOI: 10.1016/j.spc.2022.01.010
Števko, P., Kohár, R., Cechmánek, D., Medvecká, D., and Nový, F., 2023. Optimization of the tire building drum for passenger tires using the TRIZ methodology. Management Systems in Production Engineering, 31(3), 361–372, DOI: 10.2478/mspe-2023-0040.
Sumarno, S., Badriyah, S., and Hartomo, D. D., 2016. Inovasi Produk Kerajinan Pengolahan Limbah Padat (Recycle) Industri Pengolahan Kayu Jati dan Upaya Mensinergikan Sentra-sentra Industri Kerajinan di Kabupaten Klaten, Laporan Akhir Program Hi-Link Tahap III.
Sutarman, I. W., 2016. Pemanfaatan limbah industri pengolahan kayu di kota Denpasar (studi kasus pada CV Aditya). Penelitian dan Aplikasi Sistem dan Teknik Industri, 10(1), 182888.
Tang, C., Xue, Y., Wu, H., Irfan, M., and Hao, Y., 2022. How does telecommunications infrastructure affect eco-efficiency? Evidence from a quasi-natural experiment in China. Technology in Society, 69, 101963, DOI: 10.1016/j.techsoc.2022.101963.
Ulrich, K., and Eppinger, S., 2011. EBOOK: Product Design and Development. McGraw Hill.
UNCTAD, 2004. A manual for preparers and users of Eco-efficiency Indicators. New York.
UNEP, 2004, UNEP annual report 2003. Retrieved January 23, 2022, from https://digitallibrary.un.org/record/520753
Vanko, K., Pompáš, L., Madaj, R., Vicen, M., and Šutka, J., 2023. Optimization of assembly devices of automated workplaces using the TRIZ methodology. Production Engineering Archives, 29(3), 231–240, DOI: 10.30657/pea.2023.29.27.
Vieira, J., Osório, J. M. A., Mouta, S., Delgado, P., Portinha, A., Meireles, J. F., and Santos, J. A., 2017. Kansei engineering as a tool for the design of in-vehicle rubber keypads. Applied Ergonomics, 61, 1–11, DOI: 10.1016/j.apergo.2016.12.019
Vinodh, S., Kamala, V., and Jayakrishna, K., 2014. Integration of ECQFD, TRIZ, and AHP for innovative and sustainable product development. Applied Mathematical Modelling, 38(11–12), 2758–2770, DOI: 10.1016/j.apm.2013.10.057
Vinyes, E., Oliver-Solà, J., Ugaya, C., Rieradevall, J., and Gasol, C. M., 2013. Application of LCSA to used cooking oil waste management. The international journal of life cycle assessment, 18(2), 445–455, DOI: 10.1007/s11367-012-0482-z.
Vogtlander, J. G., Scheepens, A. E., Bocken, N. M. P., and Peck, D., 2017. Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing. Journal of Remanufacturing, 7(1), 1–17, DOI: 10.1007/s13243-017-0031-9.
Wang, C.-H., 2020. Incorporating user preferences and performance ratings into multi-functional tablet design and recommendation. International Journal of Industrial Engineering, 27(2), 308.
Wang, L., Bai, J., and Wang, H., 2020. The Research on eco-design and eco-efficiency of life cycle analysis. IOP Conference Series: Earth and Environmental Science, 440(4), 1–8, DOI: 10.1088/1755-1315/440/4/042042.
Wang, W., Wang, H., Liu, G., and Gao, L., 2022. Analysis of the trade-off between hydroelectricity generation and ecological protection from the perspective of eco-efficiency in Southwest China, Journal of Environmental Management, 315, 115063, DOI: 10.1016/j.jenvman.2022.115063
Wang, Y.-H., Lee, C.-H., and Trappey, A. J. C., 2017. Service design blueprint approach incorporating TRIZ and service QFD for a meal ordering system: A case study. Computers & Industrial Engineering, 107, 388–400, DOI: 10.1016/j.cie.2017.01.013
WBCSD, 2006. Eco-efficiency Learning Module. World Business Council for Sustainable Development (WBCSD), Five Winds International. Retrieved from https://www.wbcsd.org/Projects/Education/Resources/Eco-efficiency-Learning-Module
Wever, R., and Vogtländer, J., 2013. Eco-efficient value creation: an alternative perspective on packaging and sustainability. Packaging and Technology and Science, 26, 229–248, DOI: 10.1002/pts.
Wicaksono, P. A., Sari, D. P., Azzahra, F., and Aini, N., 2024. Analysis of consumer behaviour in purchasing second-hand fashion products : an extended theory of planned behaviour model. International Journal of Sustainable Development and Planning, 19(8), 2955–2964, DOI: 10.18280/ijsdp.190813
Wong, Y. L., Lee, K. M., and Yung, K. C., 2010. Model scenario for integrated environmental product assessment at the use of raw materials stage of a product. Resources, Conservation and Recycling, 54(11), 841–850, DOI: 10.1016/j.resconrec.2010.01.003
Yang, C. J., and Chen, J. L., 2011. Accelerating preliminary eco-innovation design for products that integrates case-based reasoning and TRIZ method. Journal of cleaner production, 19(9–10), 998–1006, DOI: 10.1016/j.jclepro.2011.01.014

Yang, T.-H., Lin, C.-J., Wang, S.-Y., and Tsai, M.-J., 2007. Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin. Building and Environment, 42(1), 189–195, DOI: 10.1016/j.buildenv.2005.08.028
Zhang, J., Chai, K.-H., and Tan, K.-C., 2003a. 40 inventive principles with applications in service operations management. The TRIZ Journal, 8(12).
Zhang, J., Tan, K.-C., and Chai, K.-H., 2003b. Systematic innovation in service design through TRIZ. The TRIZ Journal, 9(1), 1013–1022.
Zhang, X., Badurdeen, F., and Jawahir, I. S., 2013. On improving the product sustainability of metallic automotive components by using the total life-cycle approach and the 6R methodology, 11thGlobal Conference on Sustainable Manufacturing, Berlin, Germany, 194–199.
Zhang, Y., Mao, Y., Jiao, L., Shuai, C., and Zhang, H., 2021. Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. Environmental Impact Assessment Review, 89, 106580, DOI: 10.1016/j.eiar.2021.106580

Appendix

Table 5. TRIZEE design tools

Concept Element	Eco-efficiency element	TRIZ Principle
Unity	TR: Combining pieces of wood as raw material	#2 Taking out Replace regular adhesive with non-toxic adhesive.
	ER: Use of electricity for the material-cutting process	#26 Copying The electrical energy consumption of the waste chip splitting machine is smaller than that of the log sawmill machine
	MR: Using wood waste as raw material	#1 Segmentation Cut wood waste in the form of pieces into small blocks #26 Copying Multiply small blocks #5 Merging Combining pieces of small blocks into block boards
	RC: Putting together waste wood scraps to make products	#22 Blessing in disguise or turn lemon into lemonade Optimizing existing resources by utilizing wood waste
Multi-function	MR: Create one product with many functions	#6 Universality Making a part or object perform multiple functions will reduce material usage.
	RS: Apart from being a table, the product is also used as a place to store goods.	#3 Local quality. Has different and useful functions #3 Local quality. Table with additional storage in the form of drawers #3 Local quality. Storage in the form of a cupboard #7 Nested doll Place the cupboard inside the table #7 Nested doll Place a retractable drawer on the table #7 Nested doll The size of the cupboard is adjusted to the size of the table #7 Nested doll The size of the drawer is adjusted to the size of the table
Minimalist	TR: Product coloring	#2 Taking out Replacing ordinary dyes with environmentally friendly dyes
	MR: Use resources efficiently	#34 Discarding and recovering Eliminate unimportant parts, thus saving raw materials